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THE ANODE MECHANISM OF A THERMAL ARGON ARC

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**SUMMARY** In order to clarify the anode mechanism in freely burning argon arcs, the anode drop was determined by probe measurements in the current intensity range of 10 to 200 Amp and arc lengths between 2 and 10 mm. Simultaneously, the power input at the anode was determined by measuring the temperature increase in the cooling water, using a thermoelement, and compared to the electrical output at the arc and in the anodic drop area. An anodic contraction was observed in the arc, at low current intensities. The results can be explained in terms of the effects of a cathodic plasma current, and in the contracted arc, in terms of an additional anodic plasma current.

\*

## I INTRODUCTION

In two earlier publications [3,4]\*\*\* we described the

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\* Dedicated to Prof. Dr. M. Czerny and Prof. Dr. F. Hund on his 60th birthday

\*\* Numbers in the right margin indicate foreign pagination

\*\*\* Subsequently referred to as I and II

temperature and voltage behavior of large-current arcs between cooled metal electrodes in argon and nitrogen, as well as the dependence of the anodic drop above 50 Amp on arc length and current intensity. We had found the expression

$$U_A = A - BT$$

to relate the anodic drop  $U_A$  and the axial temperature  $T$  of the plasma before the anode, in the argon arc, where  $A$  and  $B$  are constants independent of the arc length and current intensity. We had attempted to interpret this result by means of an anode mechanism [8], to correspond to Ecker's cathode mechanism. According to Ecker, a substantial fraction of the charge carriers in the plasma before the cathode are caused by thermal ionization; the column is so severely contracted here, that the necessary carriers can be supplied by the temperature increase accompanying the contraction. Ecker has calculated the relationships [5,6] and suspects that the situation is similar at the anode [7]; less energy is required here for ionization, because only the few positive ions necessary to compensate the space charge of the electron current flowing towards the cathode have to be replaced. Meanwhile Maecker [10] has shown, using the example of the large current carbon arc, a plasma current towards the anode is generated in arcs with cathodic contraction, which occasionally can completely prevent ion drift towards the cathode. In our cathodically very contracted high temperature arcs, this effect should certainly be taken into consideration. To further clarify the anode mechanism, we therefore expanded our earlier measurements of the anode drop in argon arcs to the range of lower current intensities, as well as measuring the power transported to the anode, as a function of current intensity and arc length. /245

## II EXPERIMENTAL SECTION

Our arc geometry was that described in I, except that instead of the spherical anode we used a copper plate water-cooled from beneath (Figure 1, below). Since the anodic drop to some extent

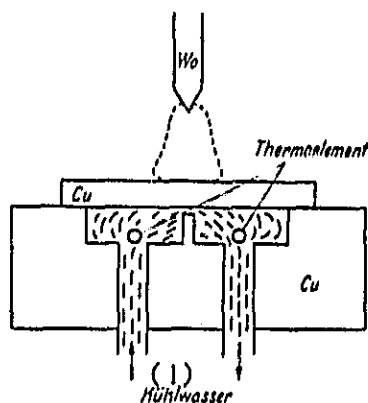


Fig. 1. Schematische Anordnung des Bogens

KEY 1 Cooling water

Figure 1 Schematic of the arc geometry

depends on anode temperature, the values measured at this differently cooled anode differ by 1 to 2 V from our earlier measurements.

In analogy to the method used in II, the anodic drop was determined by plasma voltage measurements at approximately 1 mm in front of the anode, using a 0.3 mm thick tungsten probe, at current intensities between 10 and 200 Amp and arc lengths between 2 and 10 mm.

To measure the power input at the anode, the two soldering points of a nickel-chromium-constantan thermoelement were placed in the in and outflowing cooling water stream under the anode plate, as shown in Figure 1, to determine the water temperature

increase. In conjunction with the water flow per unit time it was possible to calculate the heat dissipated at the anode.

The anodic spot was examined under amplification and the current density computed from the visible diameter.

The burning voltage was measured in all experiments, insuring that the voltage drop between the current supply and the electrode surface was negligible.

### III RESULTS

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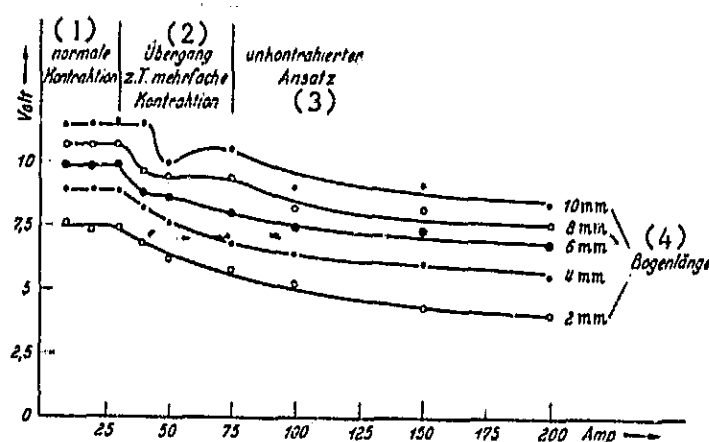


Fig. 2. Abhängigkeit des Anodenfalles von der Stromstärke für verschiedene Bogenlängen

KEY 1 Normal contraction 2 Transition to multiple contraction, in part 3 Uncontracted spot 4 Arc length

Figure 2 Dependence of the anodic drop on current intensity at various arc lengths

Figure 2, above, shows the dependence of the anodic drop on current intensity at various arc lengths. In the range to approximately 30 Amp  $U_A$  is independent of the current intensity;

at higher current intensities it shows the decrease already found in II. In both ranges the anodic drop increases with increasing arc length. Figure 3, below, shows the anodic drop for three fixed current intensities, as a function of arc length.

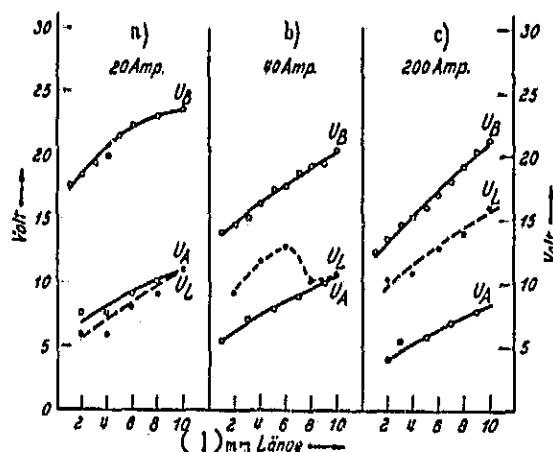


Fig. 3 a-c. Abhängigkeit des Anodenfalles  $U_A$ , der Brennspannung  $U_B$  und der zur Anodenleistung erforderlichen Spannung  $U_L$  von der Hugenlänge für verschiedene Stromstärken

KEY 1 Length, mm

Figure 3a-c Dependence of the anodic drop  $U_A$ , the burning voltage  $U_B$  and the voltage  $U_L$  required for anodic output on the arc length, for various current intensities

We also determined the power input at the anode, in watts, for the current intensities and arc lengths indicated. From it was subtracted the energy per second released as heat during the neutralization of the electrons. The rest, which we shall subsequently refer to as anodic output, was divided by the current intensity for better comparison with the anodic drop voltage, thus determining the voltage  $U_L$  required, at a given current intensity, to generate that output. It is shown in Figure 3, above, together with the anodic drop and the burning

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voltage, for three typical current intensities, as a function of arc length. This result can be expressed by the statement that there is a horizontal plane in the arc (cf. Figure 1) below which all of the electric energy that is converted reaches the anode as thermal energy. Its position is determined by its potential difference with respect to the anode being equal to the voltage required for the anodic output.

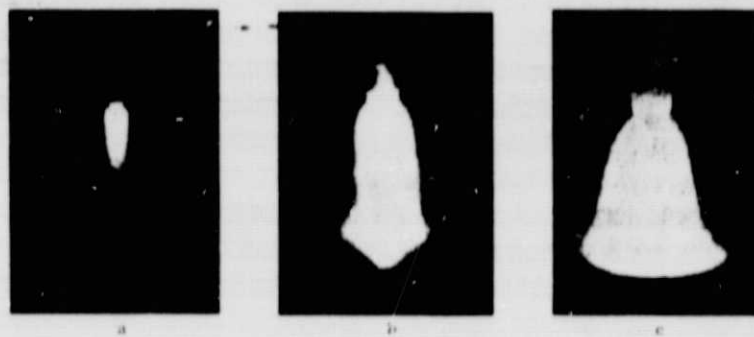


Figure 4a-c a,b: Images of the contracted arc, at 16 Amp (different exposure times). c: uncontracted arc at 200 Amp

The anodic spot shows a contraction of from 1 to 2 mm for all arc lengths, at current intensities up to 30 Amp. At constant arc length, in this area the estimated current density before the anode is independent of the current intensity. At constant current intensity the current density decreases with increasing arc length. In the range above 75 Amp the anodic spot is not contracted, at all lengths investigated. Figure 4, above, shows two examples of the contracted arc at 16 Amp (under weak and strong illumination), as well as an example of the uncontracted spot at 200 Amp. Here, the arc diameter before the anode can take values of up to 10 mm. In this range, at constant arc length the current density increases with increasing current intensity, and at constant current intensity it increases with



decreasing arc length. The transition from the contracted to the uncontracted arc occurs gradually, over a current intensity range of approximately 5 Amp. At the greater arc lengths, in a transition range between 30 and 75 Amp, suddenly several spots may appear, which rapidly move towards the anode, changing constantly. In that case the arc burns very unsteadily. /248

At intermediate arc lengths, between 10 and 30 Amp, the burning voltage decreases from approximately 30 V to 15 V. At higher current intensities it shows the course indicated by us in I, with a gentle decrease to approximately 100 Amp and a slow increase towards the higher current intensities.

#### IV DISCUSSION

We have called anodic drop, here, the voltage decrease over the last mm of the arc, measured with probes, even though usually the anodic drop area is considered to be much more restricted. Thus Block and Finkelburg [2] have shown experimentally and Bez and Hoecker [3] theoretically that for a field ionization mechanism the anodic drop region extends over only a few path lengths. From theoretical considerations we do not expect such a clearly defined drop area for our high temperature arcs. Hoecker had already pointed out that the thermal mechanism entails a more extended transition region that can not be precisely delimited from the column. In it the field intensity slowly rises, from the column onwards, to attain values so far above the column field intensity that it is appropriate to consider the decrease in potential across this extended region as anodic drop. In contrast to the slow change in potential in front of the anode, the axial temperature falls from its maximum value of approximately 15,000°K to the temperature of the cooled anode over a distance of at most 0.1 mm. In the non-contracted

arc, the initial temperature is that of the column, while in the contracted arc the plasma temperature in the contracted region rises above the column temperature, as can be seen from the increased luminous density. Figure 4a shows this in a picture of an anodically contracted arc at 16 Amp.

The measured behavior of the anodic drop becomes qualitatively understandable if we take into consideration the plasma currents, temperature and ionization.

We shall discuss arcs with anodic contraction first. Since according to Maecker [10] a plasma current issues in axial direction from each contraction site, in an anodically contracted plasma we must take into consideration plasma currents from the cathode and from the anode. These currents meet at approximately 1 mm from the anode, generating a kind of plate, as described by Maecker, in which the plasma is directed outwards (cf. Fig. 4b). The anodic current pulls neutral gas into the plasma, which must be ionized. According to our measurements, this ionization occurs purely thermally, since the potential drop - which in this case is measured between the /249 plane of the plate and the anode - always remains below the ionization potential. The anodic current density and hence the temperature in front of the anode is independent of current intensity. Therefore - and in agreement with our measurements - the voltage drop necessary to maintain the "ionization temperature" is also independent of current intensity, over this region. As the arc length becomes greater, the effect of the cathodic current becomes weaker, with respect to that of the anodic one, because according to Wienecke [12] the current velocity decreases very rapidly with the distance from the cathode and hence this effect overshadows the slower decrease in anodic current due to the decreasing anodic current density. Thus the anodic current pushes the plate farther away from the anode and causes an additional ion loss in axial direction,

which will be larger the greater the arc length is, i.e., the weaker the influence of the cathodic current is. Thus, in accordance with our findings, the anodic drop must increase with increasing arc length. If the current density is changed, at large and constant arc lengths, then the anodic drop does not change, because anodic and cathodic currents change to the same extent, the plate remains at the same distance from the anode, and hence the axial ion loss also remains constant.

Anode output measurements show that in the contracted arc (cf. Fig. 3a) nearly the power converted in the anodic drop reaches the anode. In this interpretation we start from the finding, confirmed by many authors, that for arcs that do not radiate much, the power loss due to heat conduction predominates by far over all other losses. However, in front of the anode the power is transported almost exclusively to the anode by heat conduction. This is due to the fact that there is a region of raised temperature right in front of the anode and hence no thermal energy can be transported across this temperature maximum towards the cathode. This effect had already been described by Bauer and Schulz [1] for the corresponding conditions at the cathode. Since in addition the axial temperature gradient is substantially larger than the radial one in front of the anode, radial heat conduction can play only a subordinate role. However due to their relatively great scatter, the fact that in our measurements the measurement points for anodic output - or respectively, those for the potential necessary to generate it - lie somewhat below the anodic drop voltage, can not be attributed with certainty to the radial energy losses.

In the anodically uncontracted arc we observed an anodic drop that decreased with increasing current intensity  $I$  and current density  $j$ . This fact can essentially be explained in terms of the cathodic current. The latter is stronger the greater  $I$  and  $j$  are [10] and finally becomes so strong that no ions can

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flow towards the cathode any longer and hence must be replaced. Hence, in this limiting case an anodic drop is no longer necessary for ion replacement. While the field intensity - and thereby the acceleration of the ions in the field before the anode - increases quite readily between 100 and 200 Amp according to II, this effect is small in comparison to the increasing repelling force due to the current. As was the case for contracted arc, as the arc lengthens, the effect of the cathodic current becomes weaker. It must furthermore be considered that at higher current density there is also a temperature increase in front of the anode, which already makes the ions flowing away against the current easier to replace thermally. What role is played by this empirically found dependence of the anodic drop on the temperature could not be calculated to date, because of lack of adequate knowledge of the plasma data immediately before the anode. The fact that fewer ions can flow towards the cathode as the cathodic current becomes stronger with increasing current intensity is undoubtedly very decisive for the decrease in anodic drop with increasing current intensity.

In the case of the non-contracted arc, much more than the power converted by the anodic drop reaches the anode (cf. Fig. 3c). This is based on an effect predicted by Maecker [11]: due to a convection related to the plasma current, nearly the entire power dissipated by radial heat conduction is eventually returned to the anode. Essentially only the thermal power\*

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\* Part of the energy flowing towards the cathode from the cathodic fall is used for electron emission and transported to the anode again by the electrons as exit energy. But this quantity was subtracted from our measurements; we disregarded the difference in work function between tungsten and copper, since due to the higher temperature it is more strongly lowered than in copper.

converted in the cathodic drop and the radial loss by radiation do not reach the anode. Extrapolation of the curves  $U_B$  and  $U_L$  in Figure 3c to arc length 0 leads to agreement with our earlier estimate (I) of a cathodic drop of approximately 4 V. The low increase in the difference  $U_B - U_L$  by approximately 2 V, with increasing arc length, could be attributed to radial radiative loss, which increase with the lengthening of the arc column. It was identified in several measurement series, albeit with a scatter of the same order of magnitude as the effect itself; hence, no far-reaching conclusions should be drawn from it.

With regard to the transition zone between arcs with and without anodic contraction - which lies between 30 and 75 Amp - there is little to be said. An arc of 2 mm in length, for instance, is clearly non-contracted at 40 Amp. The anodic drop clearly shows the behavior of the non-contracted arc. At greater arc length transition manifestations occur, while a 10 mm long arc is already clearly contracted, with its anodic drop in the constant region. Figure 3b shows an example for the anodic output at 40 Amp. At small arc lengths it lies considerably above the anodic drop output, falling nearly to the value of the latter as contraction sets in. /251

It was not possible to perform similar studies on the nitrogen arc because it burns too unsteadily for precise measurements at low current intensities. Only anodic output at high current intensities (100 to 200 Amp) was determined. In analogy to the argon arc, here approximately 60-80% of the arc power reached the anode. At lower current intensities it was also possible to observe anodic contraction. It may be assumed that no qualitative difference exists in the anodic mechanism between argon and nitrogen arcs, i.e., that also in the case of the latter the plasma currents decisively affect the anodic drop and anodic output.

We would like to thank Miss B. Mieth for assistance with the measurements on which this paper is based, and Dr. Maecker for informative discussions.

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